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Targets intended to produce ignition on NIF are being simulated and the simulations used to set specifications for target fabrication. Recent design work has focused on refining the designs that use 1.0 MJ of laser energy, with ablators of Be(Cu), CH(Ge), and diamond-like C. The main-line hohlraum design now has a He gas fill, a wall of U-Au layers, and no shields as were formerly used between the capsule and the laser entrance holes. The emphasis in this presentation will be on changes in the requirements over the last year, and on the characteristics of the diamond-ablator design. Complete tables of specifications have been prepared for all of the targets. All the specifications are rolled together into an error budget indicating adequate margin for ignition with all of the designs.

I. INTRODUCTION

This article is an update on our use of simulations and analysis to set requirements for the ignition experiments to be done on the National Ignition Facility.[1] The targets are very similar to those described previously.[2,3,4] They are intended to produce thermonuclear ignition and burn, using 1.0 MJ of laser light in 2010. We describe the update of the point design, from the previous design designated Rev0 to the new Rev1. Rev0 was essentially the same as described in Ref. 3, although at that time the design had not yet been named and put under configuration control. Specifics of the current point design Rev1 are described in Section II. Since the purpose of this article is to describe the update in the design, the detailed discussion in Section II is primarily of those things that were changed in the recent update from Rev0 to Rev1. After Rev1 was defined, further analysis is already suggesting some issues that need to be looked into further, and possibly revised in the next update. These issues are discussed in Section III. In Section IV we describe alternate ablators that are being kept as contingency backups.

II. DESCRIPTION OF THE POINT DESIGN

One design is designated as the point design because it is currently thought to represent the best tradeoff of fabrication, laser, and performance issues. The overall target configuration is shown in Fig. 1, and a detail of the capsule in Fig. 2. The hohlraum shown in Fig. 1 differs from the design presented at the last target fabrication meeting primarily in that the new design does not have shields between the capsule and the laser entrance holes. The decision to remove the shields was not based on any single factor, but was a judgment based on the overall balance of symmetry, laser-plasma interactions, hohlraum efficiency, and fabrication complexity. The hohlraum is made up of 75:25 U:Au "cocktail" mixture, with a 0.5 µm-thick inner Au layer. The point design capsule is a beryllium ablator with layers of various copper doping, over a solid DT layer. The justification for the layered dopant is described in Ref. 4.

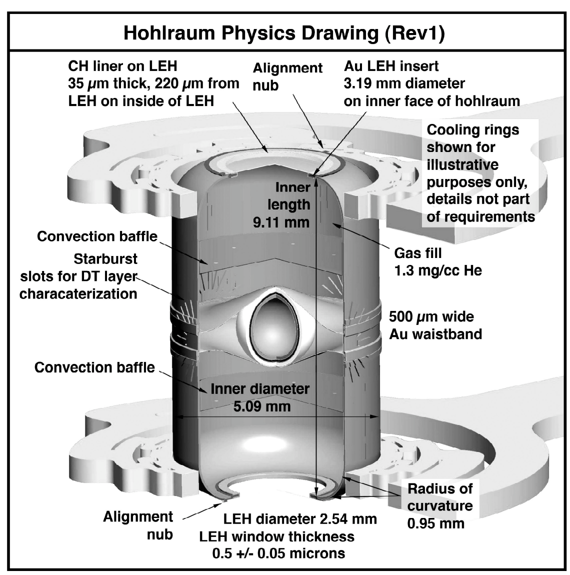

Figure 1. Configuration of the point design target.

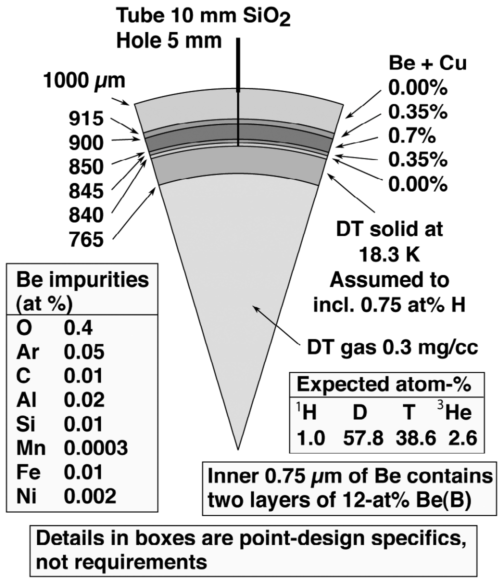

Figure 2. Pie diagram of point design capsule, showing dimensions and compositions.

Nominal compositions (shown in Fig. 2) are based on data from and experience with actual materials. The gas in equilibrium over equimolar DT was calculated by Sanchez[5] to be deuterium rich as indicated. The specification for Be impurity composition is based on measurements of early production shells by Huang.[6] Their upper limits are given in three groups — argon, oxygen, and the rest — to be consistent with actual measurement techniques. The indicated shell composition is nominal; the actual requirement only limits their total x-ray absorption to less than 30% above pure Be.[7] Argon is specified separately because of an absorption edge in the measurement energy band. The specified oxygen level (<1 at%) is a goal for target fabrication; exceeding that costs margin or increases required drive energy. Two layers of 12 at% B-doped Be have been added to the innermost layer to seal the shell against D-T permeation.

Specified low mode power spectra have also been changed. The earlier design used to determine the Rev0 specs was insensitive to mode 4 fluctuations — the growth on acceleration was canceled on deceleration so net growth was zero — so the Rev0 mode 4 spec was quite generous. Design changes have shifted that insensitivity to another mode, making it overly generous at mode 4. The Rev1 specification is tight enough to be insensitive to the actual location of that zero point. Feedback we get from target characterization indicates that the new requirement will not present particular difficulty.[8] In addition, formulae have been developed for treatment of correlations between radius and thickness fluctuations.

Predicted performance, assuming all of the deviations from imperfection, is simulated in 1D and 2D with the codes Lasnex[9] and Hydra.[10] (Hydra can also do 3D simulations, and in the past has been used to verify our understanding of the connections between 2D and 3D analysis. No 3D simulations are discussed here.) In 1D simulations, we have done multi-variable-sensitivity analyses where we vary the parameters as multipliers on the specifications, both one at a time and all together per a statistical ensemble. The 34 1D perturbations include capsule dimensions, densities, compositions, and features of the x-ray drive. This work indicates that the overall margin for 1D perturbations is about 80% — that is, if all of the requirements were loosened by a factor of 1.8, then on the average we would predict a 50% probability of 50% of clean yield. It is approximately the quadrature sum of all 34 perturbations that determines this performance, so any one of the deviations can be considerably larger, depending on its individual margin. The items with the smallest margin according to this analysis are: the 100 ps timing uncertainty of the 4th rise of x-ray pulse, with a safety factor of 3.1 assuming all other perturbations are at nominal; the level of the first shock, with safety factor 4.3; and a number of items with safety factor 5.1 — the Cu fraction in the most heavily doped layer, the amount of oxygen in the beryllium, and the level of the 4th rise.

Specifications on voids and opacity variations have been set by assuming that the variations are random. If voids are randomly located, have a characteristic volume v, and add up to void fraction f, then the effect on the implosions is proportional to fv. The Rev1 spec is that fv be less than $(0.03)(0.1\mu m^3)$. It appears that the void fraction will be about 0.06, in which case the typical void volume is to be less than $0.05\mu m^3$. Precision radiography (see Eddinger's paper in this volume) will constrain the void size and density, although to fully verify the specification it may be necessary to do dedicated experiments with thin uniformly doped or undoped shells. Modulations in composition, and the roughness of the internal layers, also affect the radiography and are likely to dominate the void contribution in the case of full thickness shells with layered dopant levels. If voids are not randomly located, the principal impact on performance will be via the resulting variations in column density, which would also be evident in precision radiography.

In 2D, simulations have been done with all of the surface perturbations set at their nominal surface power spectra. These have been done with both all-nominal 1D parameters, and with the 34 1D parameters having statistically sampled deviations from nominal. This analysis turned up a problem with the Rev1 requirements: the internal interfaces in the layer-Cu dopant had too loose of a requirement. Based on feedback from target fabrication experts,[8] and the simulations, it should be straightforward to define and meet a tighter requirement. The work described below assumed the Rev1 spec for the innermost internal layer, and then let the subsequent layers get rougher by factors of 2, 3, and 4 (in power), while Rev1 allows factors of 6.25, 12.5, and 25.

With these modified Rev1 surface perturbations, nominal Rev1-spec ice perturbations, and all of the nominally allowed variations in 1D parameters, we find that the probability of getting yield more than 6 MJ in a statistical ensemble of simulations is 80%, and there is a 90% probability of getting at least 1 MJ. While these probabilities are high enough to be encouraging, they do suggest that at 1.0 MJ we do not have very much margin remaining. These calculations do not include hohlraum asymmetry or power balance errors, which are expected to be significant factors in the overall margin. One special concern is the ice features, where there is not yet very much data ensuring that the specification can be met for the ice roughness in beryllium.

III. POSSIBLE FUTURE MODIFICATIONS TO THE POINT DESIGN

There are three issues that we are pursuing that may result in modifications to the Rev1 design.

First is our desire to increase margin against laser-plasma instabilities (LPI). As our understanding of LPI and how to estimate them improves, from Omega experiments and calculational progress, it appears that the 300eV point design may not have as much margin against LPI as we would like.[11] Some changes in the design can reduce LPI without requiring more laser power or energy: making the laser spots as big as possible given the other constraints on hohlraum performance, optimizing the hohlraum efficiency in order to minimize laser power, and optimizing the bandwidth and SSD features. These optimizations have generally already been carried as far as possible, and do not affect the target fabrication plans. (One possible change, which was not mentioned at the meeting but has been discussed before the time of this writing, is including a few at% boron in the gold hohlraum lining.) Any further changes to the design to reduced LPI will increase the requirements on power, energy, or both, and will result in incremental changes in the target geometry. These could include changing the laser entrance hole size, increasing the size of the hohlraum, or changing the peak hohlraum temperature. This last change would require larger hohlraums and capsules, possibly by a factor of 1.3, while the capsule is relatively thinner (not much different from the current 160 micron thickness).

Second, as mentioned above, there is concern that the DT ice roughness will not meet the Rev1 specs, or that unacceptable cracks will be present. (The Rev1 specs do not really specify an allowed crack size, although cracks would be constrained formally by the void specification. We estimate that cracks larger than about 50 square microns in cross sectional area would be large enough to be of concern. This is considerably larger than the void specification in Rev1, but comparable to estimates of how large cracks might be.) If the ice quality is significantly worse than the current requirements, the program would have two options. First, we could change the operating temperature to be closer to the triple point, which would presumably make the ice smoother. Since targets' performance is less robust at higher operating temperature, we would need to increase the scale of the target in order to recover acceptable margin. The other option would be to increase the target size, keeping the operating temperature fixed, so that it becomes sufficiently robust to tolerate the expected ice roughness. Either of these options would require increasing the power and energy required from the laser.

Third, there are a number of issues that are currently under investigation that affect the specification for the inner surface of the beryllium, and for how well the ice conforms to the beryllium. The growth of perturbations seeded at this interface is primarily at very high modes (500-2000), and is sensitive to details of the thermal conduction between the hot beryllium, which absorbs preheat X-rays, and the cooler DT. The growth is on a gradient on the outer edge of the accelerating DT, which has a scale length set by the thermal conduction. Because of this sensitivity, we are striving to ensure that the thermal conduction model we use is as accurate as possible. Another issue is the character of the perturbations. Past work assumed the roughness on the inner surface to be homogeneous, but recent spherical interferometer data indicates that the roughness may be dominated by small patches that are significantly rougher than the overall power spectrum would indicate.[8] We are doing 3D simulations of such patches to determine an appropriate requirement. Finally, there is the issue of how the ice conforms to the beryllium, which is currently spec'd very tightly. It would be valuable to have some estimates of how nonconformal the ice might be, and of how that could be measured. This would form the basis for an improved specification.

These variations on the point design will be folded into upcoming updates of the requirements tables. In January 2007 there will be a relatively minor update designated Rev1a. This will include the internal interface roughness as described above, and might include a modification to the Be inner surface requirement, but will mostly update laser issues and auxiliary documentation such as stakeholder approval and sensitivity tabulation. In March 2007 a major update, Rev2, will be released which will be a new overall balance of the issues described above. Further updates, based on analysis and Omega experiments, will proceed until early NIF experiments, possibly in 2008 with 96 beams. Results of these experiments will allow for one last optimization before all details are defined going into the ignition experiments in 2009 and 2010.

IV. ALTERNATE ABLATORS

At this time there are three alternate ablators that are considered to remain as options: CH(Ge), high density C, and uniformly doped Be. (Regarding the hohlraum, there are alternates being maintained in the documentation but no real work is going into them and effectively the downselect decision has already been made.)

The CH(Ge) design and the uniformly doped Be design have not changed formally since previously described[3] and little work has been done on them. Progress in our general understanding suggests that a 1.0 MJ CH design would be quite marginal. In particular the ice would probably be rougher than could allow for acceptable performance. A viable CH(Ge) design, with expected ice roughness, would probably require 1.3 to 1.5 MJ of laser energy, and be 10-15% bigger in linear dimensions than the design shown in Ref. 3. The uniformly doped Be design is being examined by our colleagues at Los Alamos and is not described here.

High-density carbon continues to be attractive as a possible ablator. The design is only slightly different from that shown in Ref. 3 — the C shell is now 87.5 μm thick, and undoped, rather than the thinner doped shell in Ref. 3. The most important issue for the C design is the potential for perturbations arising out of the material structure, especially those that might arise during the melt history. Current strategy is to keep the material solid after the first shock, and to melt it with the second shock. There may also be LPI issues with the carbon ablator filling the hohlraum. The viability of C continues to be investigated with experiments and improvements in modeling. The most important potential advantage of C is that the design can tolerate considerably rougher DT ice than can Be. The significance of this hinges on the ice characterization experiments being done in early calendar 2007.

Specifications for the C design are in the Rev1 tables. Surface roughness specifications are extensions of those for the point design. The ice roughness specification is the same as for Be at low modes, and twice as large (in amplitude) at modes above about 6. The ablator inner surface roughness is now the same as Be, although this may change depending on both solid-strength modeling and DT thermal conductivity modeling. Experiments on solid strength effects later in 2007 may be done to verify these issues. The requirements for thickness variations, and thus also for the outer surface, are about 3x smoother (in amplitude) than for Be.

The ablator down-select decision will be made around the end of FY07, based on answers to the following questions: How good is the DT ice layer in the various materials, relative to what it should be for each? How well can the ablator itself be made, relative to its specifications? Do the different pulse shape requirements stress the laser differently? How does the ablator affect the LPI projections? Do we have a good melt strategy, and verification that it will lead to good performance? And finally, how sensitive is the performance of each ablator to uncertainties in projections and modeling given experiments that have been done at that time?

V. SUMMARY

All indications are that we will be well prepared for a serious attempt at ignition in 2010. We have a point design that is quite mature, with an initial dissemination and one update completed on the detailed specifications and requirements. Some issues remain, but resolution of all of them is completely feasible, especially given the option to increase the laser energy to approximately 1.3 MJ. The biggest uncertainties at this time are covered by variations in the design: alternate ablators, and the potential to reconfigure the hohlraum to reduce LPI. Some of these will require energy, but are well-covered within an envelope of about 1.3 MJ. The year 2007 will be very important as we define all of the details of the final optimization and begin fabrication of actual ignition targets.

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